PRODUCTION OF CHONDRULES BY LIGHTNING IN THE SOLAR NEBULA? NOT SO EASY!

S.J. Weidenschilling (PSI/SJI)

The present abstract is an update of last year's, with a report of "progress" on constraining one possible mechanism for the formation of chondrules. It is generally accepted that chondrules formed in the solar nebula by transient heating events that melted aggregates of dust grains, transforming them into small (~mm-scale) spherules of igneous material. The nature and source of the heating events is obscure, but one persistent suggestion is that some sort of "lightning" or electrostatic discharge occurred (Whipple 1966, Cameron 1966, Levy 1988, Wasson 1993, Love *et al.* 1995). This idea is attractive because the formation of planetesimals involved settling of particles into a thin, dense, dusty layer in the central plane of the nebula. This layer provided an environment with high solids/gas ratio (potentially rich in dust aggregates of appropriate size to yield chondrules when melted), as well as high opacity and oxygen fugacity inferred for the chondrule-forming region. Moreover, this layer was turbulent, with turbulence driven by shear between it and the surrounding gas, which moved at a different orbital speed due to pressure support (Weidenschilling 1980, Cuzzi *et al.* 1993). A turbulent dusty medium offers the prospect of charge separation and generation of lightning. At present, arguments for and against lightning in the solar nebula are inconclusive because of limited understanding of the mechanism(s) for generating terrestrial lightning and difficulties in scaling to very different conditions in the nebular environment (Pilipp *et al.* 1992, Morfill *et al.* 1993, Love *et al.* 1995). In this project, I attempt to place other constraints on the chondrule- forming process by modeling the particle population and turbulence properties during the formation of planetesimals. Among the questions addressed are the following: Does shear-generated turbulence provide enough energy to melt a significant amount of material? Does the coagulation and settling of dust produce precursor aggregates of the appropriate size? Are chondrules concentrated by settling, or sorted aerodynamically, and accreted efficiently into planetesimals?

The tool to investigate these phenomena is a numerical code that computes the simultaneous evolution of the size spectrum and vertical distribution of a system of particles undergoing collisional coagulation and settling under the influence of gravity and aerodynamic forces. The code's features are described by Weidenschilling (1980, 1997) and Weidenschilling and Cuzzi (1993); however, it has been modified to treat two populations of particles with different properties. Primitive "matrix" material (Population I) has low density and can be shattered in collisions, while "chondrules" (Population II) are dense and strong. Pop I aggregates within a specified (arbitrarily chosen) size range can be converted to Pop II by heating events that affect some fraction of the volume of the particle layer per unit time. "Chondrules" can be accreted by Pop I bodies, and can also accrete a veneer or rim of Pop I grains; this can be converted to Pop II material by reheating. The different densities of the populations allow sorting by differential settling and accretion efficiencies influenced by aerodynamic flow around large planetesimals (Whipple 1972). The code conserves the total mass of the system while keeping track of the numbers of particles of each population and their mean composition (fraction of "other" material present as a contaminant) vs. size. It also determines the fraction of Pop II material being accreted by the largest Pop I bodies at any given time, to check for effects of sorting.

In simulations to date, the initial state is micron-sized grains of Pop I only, uniformly mixed with the gas through the thickness of the nebula. Nebular properties are chosen consistent with a low-mass disk at $r = 3$ AU. Coagulation and settling produce a dense layer of particles in the central plane. The resulting shear generates turbulence with properties consistent with the analysis of Cuzzi et al. (1993). The turbulence dissipates energy per unit mass at a rate ~V_t^3/L, where V_t and L are the velocity and size scale of the largest eddies. As the particle mass density generally exceed that of the gas in the turbulent layer, I include it in computing the energy dissipation. This turbulent energy is converted, with some efficiency ζ, into heating some fraction of the volume of the layer. To set an upper limit to chondrule production, the heating is assumed to heat the dust (and associated gas) just enough to melt it, maximizing the melted mass. Various values of ζ have been tried, including scaling it to the spatial density of particles on the assumption that the rate of charge separation scales with collision rate.

In no case with shear-driven turbulence as the energy source is a significant concentration of "chondrules" produced. The typical mass fraction of Pop II material after model time of 10^4 years is ~10^{-5} for $\zeta = 10^{-3}$. Even letting *all* of the turbulent energy be available to melt material with 100% efficiency would not produce concentrations as high as found in most chondrites. The reason for this shortfall is a lack of available energy. The turbulence is ultimately driven by the change in gravitational potential as the particles spiral inward due to drag. Moving from 5 AU to 2 AU corresponds to a difference of a few times 10^{12} erg/g, while heating silicates by ~1500 K and melting them requires ~10^{10} erg/g. Thus, one might guess that an efficiency ~1% might allow melting of a significant fraction of the total mass. However, very little of this energy is actually available to drive turbulence. As the solids spiral inward, they give up angular momentum to the surrounding gas, which flows outward, increasing its potential energy. These effects nearly balance (Weidenschilling 1980), so the net difference is small, even if the turbulence could then be efficiently converted into high-energy events ("lightning").

A general conclusion is that turbulence *driven by local shear* could not be the energy source responsible for melting chondrules. This conclusion is independent of details about the timescale of planetesimal formation or particle size distribution. It does not rule out chondrule formation in the particle layer in the central plane of the nebula, but another source of energy is required. If the entire nebula is an accretion disk, e.g., due to turbulent convection, than inward motion of the gas in the solar gravity well would release some 3 orders of magnitude more energy (although much of this would go into heating the gas). Other possible energy sources include solar activity (magnetic reconnection events; Levy and Araki 1989), shock waves in the nebula (Hood and Horanyi 1993), or generic radiative heating (Eisenhour and Busek 1995). The plausibility of these mechanisms can be investigated with the present code by appropriate parameterizations of the heating events. These must be shown to operate on timescales consistent with planetesimal formation.

References: Cameron, A.G.W. (1966) *EPSL* **1**, 93. Hood, L. and Horanyi, M. (1993) *Icarus* **106**, 179. Levy, E. (1988) in *Meteorites and the Early Solar System* (J. Kerridge and M. Matthews, Eds.), U. of Arizona Press, 697. Levy, E. and Araki, S. (1989) *Icarus* **81**, 74. Love, S., Keil, K., and Scott, E.R.D. (1995) *Icarus* **115**, 97. Morfill, G., Spruit, H., and Levy, E. (1993) in *Protostars and Planets III* (E. Levy and J. Lunine, Eds), U. of Arizona Press, 939. Pilipp, W., Hartquist, T. and Morfill, G. (1992) *Ap.J.* **387**, 364. Wasson, J. (1993) *Meteoritics* **28**, 14. Weidenschilling, S. (1980) *Icarus* **44**, 172. Weidenschilling, S. (1997) *Icarus*, submitted. Weidenschilling, S. and Cuzzi, J. (1993) in *Protostars and Planets III*, 1031. Whipple, F. (1966) *Science* **153**, 54. Whipple, F. (1972) in *From Plasma to Planet* (A. Elvius, Ed.) Wiley, 211.

Supported by NASA Grant NAGW-4406.